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J. P. Lee

Brown & Root U.S.A., Inc., Houston, Texas

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Dynamic Considerations in the Design of Paper Machine Foundations

J.P. Lee
Senior Consultant, Brown & Root U.S.A., Inc., Houston, Texas

SYNOPSIS

The design of modern paper machine foundation should consider machine frame supporting foundation and underlying soil as an integrated system. For smooth operation of the machine, quality of paper and economic reasons, a dynamic analysis of the machine system should be performed.

This paper discusses three most important factors in the dynamic analysis of a paper machine: (1) Soil-structure interaction effect, (2) frequency analysis, and (3)force-response analysis.

I. INTRODUCTION

The design of paper machine foundations is significantly different from that of static equipment foundation. Paper machine foundations must provide supports for machine frames and machine rolls. In addition, they must provide adequate rigidity to hold machine rolls in place with very little vibrations during normal operation. In recent designs, many paper machine foundation designs are governed by the rigidity rather than the strength requirement.

The unique feature in the design of paper machine foundations is that these foundations are subjected to substantial harmonic excitations during normal operation. These harmonic forces are developed when machine rolls or paper rolls with inevitable unbalances are put into a rotating motion. Since the 1960's, two changes in paper machine design, i.e. paper traveling speed and paper width, have greatly affected the dynamic considerations in the design of paper machine foundations. The paper traveling speed has increased from approximately 2500 feet per minute (fpm) to 4500 fpm and above which increased the rotating speed proportionally. Since the harmonic exciting forces are proportional to the square of the rotating speeds, the harmonic loads are increased by a factor of 3 due to the increased speed. The width of the paper has also been substantially widened to increase paper production which resulted in increasing the weight of the machine frame and reducing the rigidity of the machine frame. To compensate for the loss of rigidity, stiffer members are now used for modern machine construction. Therefore, the dynamic considerations are becoming increasingly critical in the design of modern paper machine foundations for smooth operation, quality production and economic reasons.

This paper will discuss three most important factors in the dynamic analysis of paper machine foundations, i.e., soil-structure interaction effect, frequency analysis and force-response analysis.

II. SOIL-STRUCTURE INTERACTION EFFECT

In the 1960's and early 1970's, the effect of foundation soils was generally neglected in the dynamic analysis of a paper machine. The columns were typically considered fixed at the column bases (see figure 1). Since the soils underlying machine foundations are generally flexible, this assumption neglected the soil-structure interaction effect. As a result, the system frequencies tend to be overestimated which in turn may have affected results of the analysis.

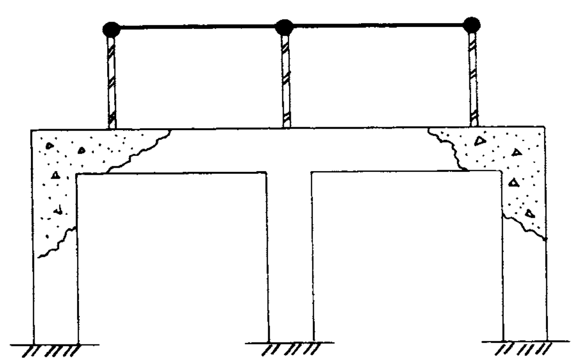

Figure 1. Paper Machine - Computer Analysis Model

In order to obtain accurate frequencies of the machine-foundation system, the effect of soil-structure interaction should be taken into account by incorporating springs representing the foundation soil into the computer analysis model for the machine foundation system (see figure 3). For spread footing supported on relatively uniform foundation soil, the equations shown in tables 1 and 2, and figure 2 can be used directly to calculate equivalent soil springs (Arya, et. al., 1981 and Richart, et. al., 1970). For Spread footings supported on layered foundations soils, equivalent soil properties must be determined before the equations can be applied.

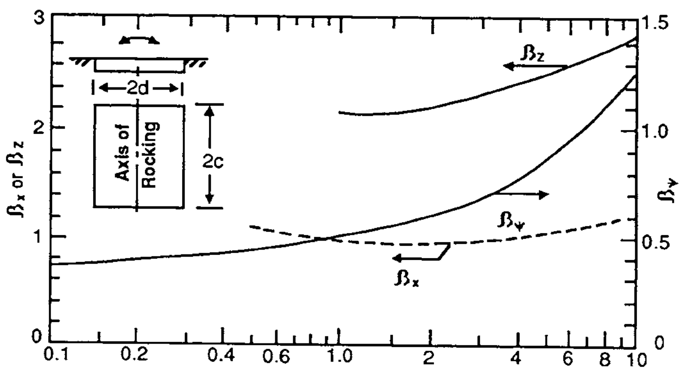

Figure 2: Coefficients β_z, β_x, and β_ψ for footings (after Whitman and Richart, 1967).

Motion	Spring Constant Embedment Factor
Vertical	$n_z = 1 + 0.6\,(1-v)\,\frac{h}{r_o}$
Horizontal	$n_{x,y} = 1 + 0.55\,(2-v)\,\frac{h}{r_o}$
Rocking	$n_{\psi,\varphi} = 1 + 1.2\,(1-v)\,\frac{h}{r_o} + 0.55\,(2-v)\,(\frac{h}{r_o})^3$

Table 2: Embedment Factors for Spring Constants

Where:

h = Embedment depth
r_o = Circular foundation radius or equivalent rectangular foundation radius (Table 3)
v = Poisson's ratio

Note: For h/r_o less than .15, embedment factors of unity shall be used.

Mode of Vibration	Circular Footing	Rectangular Footing
Vertical	$K_z = \frac{4\,G\,r_o}{1-v}\,n_z$	$K_z = \frac{G}{1-v}\,\beta_z\sqrt{4cd}\,n_z$
Horizontal	$K_{x,y} = \frac{32\,(1-v)\,Gr_o}{7-8v}\,n_{x,y}$	$K_{x,y} = 4\,(1+v)\,G\,\beta_{x,y}\sqrt{4cd}\,n_{x,y}$
Rocking	$K_{\psi,\varphi} = \frac{SGr_o^3}{3\,(1-v)}\,n_{\psi,\varphi}$	$K_{\psi,\varphi} = \frac{SG}{(1-v)}\,\beta_{\psi,\varphi}\,cd^2\,n_{\psi,\varphi}$
Torsion	$K_\theta = \frac{16}{3}\,SGr_o^3$	No Solution Available, Use Equivalent Circular Footing Equation

Table 1: Spring Constants for Rigid Circular or Rectangular Footings

Where:

G = Low strain shear modulus
c = 1/2 the foundation length parallel to rocking axis
d = 1/2 the foundation length perpendicular to rocking axis
r_o = Circular foundation radius or equivalent rectangular foundation radius (Table 3)
ß = Geometry factor for rectangular foundations (Figure 1)
n = Embedment coefficient (Table 2)
v = Poisson's Ratio

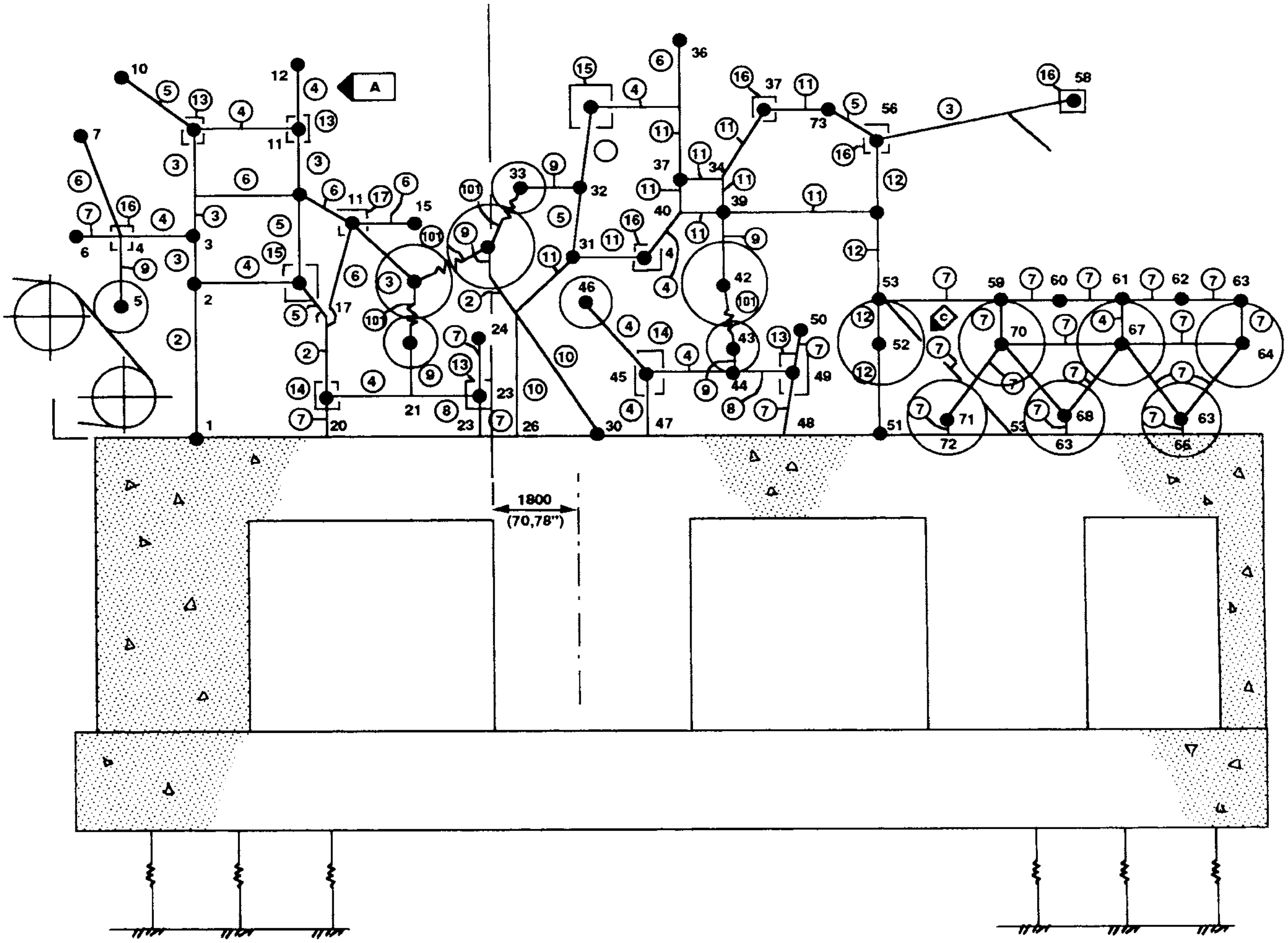

Figure 3: Computer Analysis Model (with soil springs).

III. FREQUENCY ANALYSIS

One of the most important tasks in the foundation design is to avoid a resonant condition between frequencies of major machine rolls and those of the machine-foundation system. Because if a resonant condition occurs, the responses of the machine will be greatly amplified. The dynamic amplification factor or response ratio (M) can be calculated using equation 1 (Biggs, et.al., 1964) which is shown graphically in figure 4.

$$M = \frac{1}{\sqrt{1 - \left(\frac{F_o}{F_n}\right) + \left(2D\frac{F_o}{F_n}\right)^2}} \quad \text{--EQ (1)}$$

Where:
- Fo = Operating frequency of the machine roll.
- Fn = Natural frequency of the machine-foundation system.
- D = Critical Damping Ratio.

As can be seen from figure 4, the dynamic amplification factors are substantially higher in the range of frequency ratios between 0.75 and 1.25, especially where system damping ratios are low. In order to minimize amplification of the machine responses, it is essential to keep the system to an operating frequency ratio above 1.25 (for low-tuned foundations) or below 0.75 (for high-tuned foundations). Since the paper machine may operate at any speed below the maximum design speed, extreme care should be exercised in designing a low-tuned foundation for the paper machine.

IV. FORCE-RESPONSE ANALYSIS

The ultimate purpose of the paper machine foundation is to support the machine in place without excessive vibrations during normal operation. A force-response analysis is generally required to predict the maximum response and to assure that the maximum calculated response stays within the allowable limits set forth by

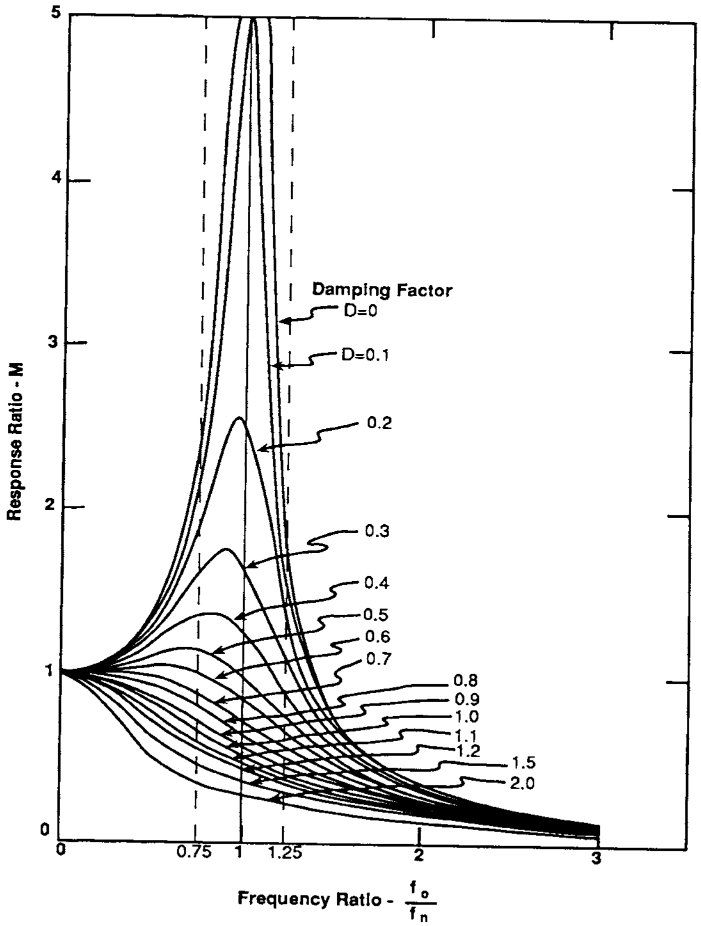

Figure 4: Response Curve for Constant Force Excitation

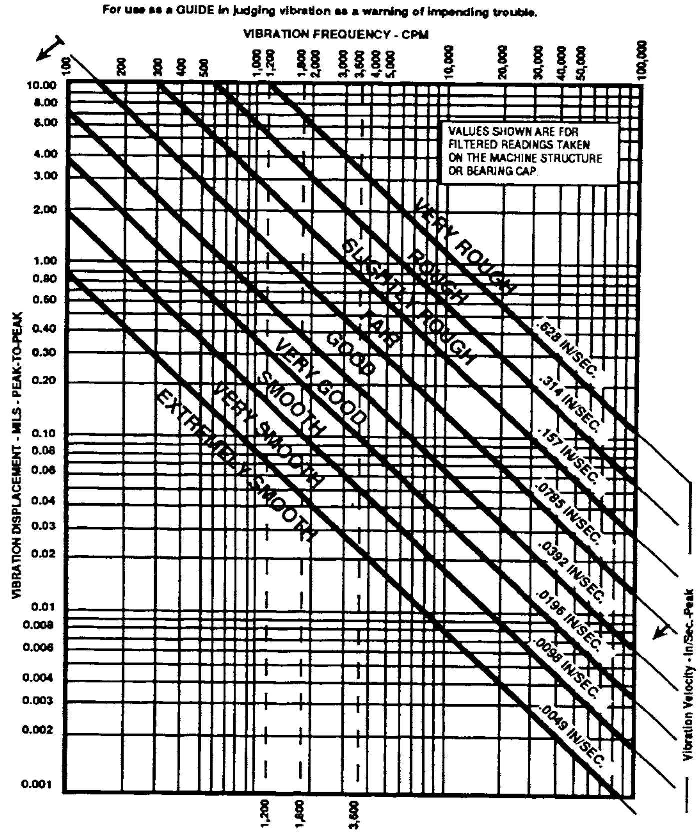

Figure 5: General Machinery Vibration Severity Chart

the paper machine manufacturer. One such set of allowable limits is shown in figure 5.

The vibration amplitudes of paper machines are greatly affected by the capacity of the system to dissipate the energy imparted by the machine rolls to its surroundings such as the foundation soil. The foundation soil is a good damping medium and should be properly taken into account by inducing its damping effects. Damping values for footings on uniform foundation soils can be determined directly from tables 3,4, and 5. However, equivalent soil properties must be determined for layered foundation soil before the equations can be applied. The calculated damping values for layered foundation soils are generally reduced by a substantial amount to account for the reflection of waves between soil layers.

In additon to the damping value consideration, the phase angle relationship among rotating rolls of the machine section is also a very important factor affecting the vibration amplitude. Since chances for the peak harmonic loads of all rolls to occur at the same time are quite remote, a combination based on a statistical approach, such as the square root of the sum of the squares, has quite often been used.

It is found that past experience of the paper machnie industry has shown that paper machines with massive, high-tuned foundations generally experience very little vibration problems and the force-response analysis are often waved based on this excellent track record. However, it is prudent to perform a force-response analysis for a low-tuned foundation especially one with a low foundation-to-machine mass ratio.

Mode of Vibration	Equivalent r_o for Rectangular Footings	Mass (or Inertia) Ratio	Radiation Damping Ratio
Vertical	$r_o = \sqrt{\frac{4cd}{\pi}}$	$B_z = \frac{(1-v)}{4} \frac{m}{\rho r_o^3}$	$D_z = \frac{0.425}{\sqrt{B_z}} \propto_z$
Horizontal	$r_o = \sqrt{\frac{4cd}{\pi}}$	$B_{x,y} = \frac{(7-8v)\, m}{32\,(1-v)\, \rho r_o^3}$	$D_{x,y} = \frac{0.288}{\sqrt{B_{x,y}}} \propto_{x,y}$
Rocking	$r_o = \sqrt[3]{\frac{16cd^3}{3\pi}}$	$B_{\psi,\varphi} = \frac{3(1-v)}{8} \frac{I_{\psi,\varphi}}{\rho r_o^5}$	$D_{\psi,\varphi} = \frac{0.15 \propto_{\psi,\varphi}}{(1+n_{\psi,\varphi} B_{\psi,\varphi}) \sqrt{n_{\psi,\varphi} B_{\psi,\varphi}}}$
Torsional	$r_o = \sqrt[4]{\frac{16cd(c^2+d^2)}{6\pi}}$	$B_\theta = \frac{I_\theta}{\rho r_o^5}$	$D_\theta = \frac{0.50}{1+2B_\theta}$

Table 3: Geometric Damping Ratios for Rigid Circular or Rectangular Footings

Where:

m = Linear mass
I = Rotary inertia
v = Poisson's ratio
n = Correction factor for B (Table 4)
ψ = Soil unit weight
φ = Soil mass density = ψ /gravitational constant
$\propto$ = Damping embedment factor (Table 5)

B_ψ or B_φ	5	3	2	1	0.8	0.5	0.2
n_ψ or n_φ	1.079	1.110	1.143	1.219	1.251	1.378	1.600

Table 4: n_ψ and n_φ Coefficients

Mode of Vibration	Damping Ratio Embedment Factor
Vertical	$\propto_z = \frac{1 + 1.9\,(1-v)\; h/r_o}{\sqrt{n_z}}$
Horizontal	$\propto_{x,y} = \frac{1 + 1.9\,(2-v)\; h/r_o}{\sqrt{n_{x,y}}}$
Rocking	$\propto_{\psi,\varphi} = \frac{1 + 0.7\,(1-v)\; h/r_o + 0.6\,(2-v)\;(h/r_o)^3}{\sqrt{n_{\psi,\varphi}}}$

Table 5: Embedment Factors for Geometric Damping Ratios

V. CONCLUSION

In the design of foundations for the modern, high speed paper machine of today, special attention should be paid to the dynamic characteristics of the machine and the foundation. The dynamic analysis of the foundation is an essential part of paper machine design to ensure smooth operation of the machine and the resulting production of quality paper. The dynamic analysis must include the following factors:

A. The soil-structure interaction effect between the machine and the foundation/soil should be properly taken into account in order to determine the system frequencies accurately.
B. The frequency analysis should be performed to avoid detrimental resonant condition between the operating frequency and the system frequencies.
C. The force-response analysis should be performed to assure that the maximum vibration amplitude are limited to within the allowables.

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